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A PROPOSAL FOR RESEARCH ON COMPLEX MEDIA, IMAGING AND UNCERTAINTY QUANTIFICATION

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14. ABSTRACT

The main accomplishments in this research project were (i) the development of a theory for virtual source imaging with passive arrays that allows imaging in very complex media using correlation based methods, and (ii) motion estimation in synthetic aperture imaging using matrix splitting methods and fast algorithms for their implementation.

15. SUBJECT TERMS

Complex media, imaging, synthetic aperture imaging, motion estimation

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Final Report for Research under Award FA9550-11-1-0266, "A PROPOSAL FOR RESEARCH ON COMPLEX MEDIA, IMAGING AND UNCERTAINTY QUANTIFICATION" for the period April 2011 to November 2013

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1 Introduction and Summary

As in the title of the research grant, our main effort is in the interdisciplinary, mathematically and computationally oriented study of imaging in complex (random) media and in the broader frontier of quantifying uncertainty. Successful research was carried out in the following areas:

- Virtual source imaging (papers 1,4,11). The idea is to use a passive array near to object to be imaged while the illumination comes from a distant array and goes through a complex and unknown medium. It is shown that when imaging with cross correlations of the data on the passive array the effects of the complex medium are minimized. This work is done mainly with J. Garnier and C. Tsogka.

- Passive sensor imaging with ambient noise sources (papers: 3,5,16,19). This work is a continuation of a project started in the previous grant period. It contains overall the following main accomplishments: (i) A demonstration that the Green's function for wave propagation in an ergodic cavity can be recovered exactly by cross correlation of signals at two points when there is only a single illuminating noise source. (ii) The systematic use of the stationary phase method to estimate travel times from recorded noise signals under different ambient noise conditions. (iii) A new theoretical formulation for imaging reflectors with passive sensors using only ambient, opportunistic

noise sources. Extensive numerical simulations amplify and validate the theory. We have also applied these methods to indoor source localization in the microwave regime using real data obtained with a source-antenna system at Stanford. One former graduate student was involved in this project (T. Callaghan) one postdoctoral visitor (N. Czink), and one senior collaborator (J. Garnier).

- Imaging in strong clutter (papers 17,20). This is continuation of research started during the previous period of the grant. It is well known that detection and imaging in strongly inhomogeneous media (heavy clutter) is very difficult if not impossible. A general and effective algorithm has been developed that can filter out and minimize clutter effects. It is based on the windowed Fourier transform (the local cosine transform) and the singular value decomposition of the sensor data. A theoretical analysis of this algorithm has been given for randomly layered media. However, numerical simulations indicate that the method works well in general clutter. One postdoctoral visitor (R. Alonzo) and two long-time collaborators were involved in this project (L. Borcea and C. Tsogka).

- Optimization based imaging (paper 2,6,12,18). This is a new project that deals with coherent imaging (imaging in homogeneous media) using optimization methods when the image space is sparse. It also includes work when only field intensity measurements are recorded by the array sensors. Semidefinite programming (optimization) methods are used in an original way to give very good results when imaging sparse reflectors and when we are in high signal-to-noise regimes. A lot more work is needed in this emerging area. The work was done with M. Moscoso (visiting from Spain), A. Chai (a former PhD student working with us) as well as L. Ryzhik and A. Novikov.

- Autofocus and motion estimation in synthetic aperture radar (paper 7,8,13). This is the continuation of a project in which we have developed autofocus methods based on a phase space formulation (Wigner transform) of the array data and the image. We have also used this approach for target motion estimation with SAR. But we have not been able so far to combine effectively autofocus methods with motion estimation. One postdoctoral researcher was involved (T. Callaghan) and one senior collaborator (L. Borcea).

- Multi-agent systems, shocks and uncertainty quantification (papers 9,10). This is a new research direction that quantifies uncertainty in multi-agent systems, using the theory of large deviations (rare events) in large, interconnected systems. We have also studied the influence of a random environment on shock propagation. This warm was done with a graduate student (T.W. Yang) and J. Garnier.

2 Graduate students, postdoctoral visitors and collaborators

Four graduate students obtained their PhD during the period of the grant: N. West 2012, (thesis on uncertainty quantification, works in the financial industry), T.W. Yang 2012 (uncertainty quantification, is now assistant professor in Minnesota), D. Shi 2013 (random matrix theory and applications, works in financial industry), M. Peng 2013 (random matrix theory, works in financial indystry). Visitors during the grant period were: J, Nolen, N. Czink, F. Guevara-Vasquez, M. Moscoso, L. Borcea, C. Tsogka, J. Garnier. Two graduate student is expected to finish in 2013 R.H Sun, (working on imaging) and L. Wang, working on uncertainty quantification).

3 Awards and major lectures

AMS J. Willard Gibbs Lecture January 2011. Honorary Doctorate, University of Paris VII, December 2011. C.C. Lin Lectures (four) at Tsinghua University, China (September 2012). Plenary lecture at the 60th anniversary of IMPA, Brazil (October 2012). Eight lectures on imaging at Tel Aviv University (June 2013).

4 Publications

All papers that are listed below and have not been published yet because they are either in the refereeing process or are accepted and on queue to appear are posted on the PI's web site: http://math.stanford.edu/∼papanico

4.1 Submitted for publication

1. Role of scattering in virtual source array imaging, J. Garnier and G. Papanicolaou, submitted for publication.

2. Imaging strong localized scatterers with sparsity promoting optimization, A. Chai, M. Moscoso and G. Papanicolaou, submitted for publication.

3. Resolution enhancement from scattering in passive sensor Imaging with Cross Correlations, Josselin Garnier and George Papanicolaou. Inverse Problems and Imaging, in revision.

4. Signal to noise ratio analysis in virtual source array imagineg, Josselin Garnier, George Papanicolaou, Adrien Semin and Chrysoula Tsogka, submitted for publication.

4.2 Publications 2013

5. Signal to noise ratio estimation in passive correlation-based imaging, J. Garnier, G. Papanicolaou, A. Semin and C. Tsogka, SIAM Journal on Imaging Science, vol 19 (2013), pp. 1092-1110.

6. Robust imaging of localized scatterers using the singular value decomposition and ℓ_1 minimization, A. Chai, M. Moscoso and G. Papanicolaou, Inverse Problems, vol 28 (2013), 105001 (21 pages).

7. Motion Estimation and Imaging of Complex Scenes with Synthetic Aperture Radar, Liliana Borcea, Thomas Callaghan and George Papanicolaou, Inverse Problems, vol 29 (2013), 054011 (29 pages).

8. Synthetic Aperture Radar Imaging and Motion Estimation via Robust Principal Component Analysis, Liliana Borcea, Thomas Callaghan and George Papanicolaou, SIAM Journal of Imaging Science, vol 6 (2013), pp. 1445-1476.

9. Large deviations for a mean field model of systemic risk, Josselin Garnier, George Papanicolaou, Tzu-Wei Yang. SIAM Journal on Financial Mathematics, vol 4 (2013), pp. 151-184.

10. Anomalous shock displacement probabilities for a perturbed scalar conservation law. J. Garnier, G. Papanicolaou and T.W. Yang. SIAM Journal on Multiscale Modeling and Simulation, vol 11, (2013), pp. 1000-1032

4.3 Publications in 2012

11. Correlation based virtual source imaging in strongly scattering media, Josselin Garnier and George Papanicolaou. Inverse Problems, vol 28, (2012), 075002 (32pp).

12. A differential equations approach to ℓ_1-minimization with applications to array imaging, M. Moscoso, A. Novikov, G. Papanicolaou and L. Ryzhik. Inverse Problems, vol 28 (2012), 105001 (21pp).

13. Synthetic Aperture Radar Imaging with Motion Estimation and Autofocus, Liliana Borcea, Thomas Callaghan and George Papanicolaou. Inverse Problems 28 (2012) 045006 (31pp).

4.4 Publications in 2011

14. Asymptotic Analysis for Periodic Structures by Alain Bensoussan, Jack-Louis Lions and George Papanicolaou, is a reprint of the 1978 *book* published by the American Mathematical Society in 2011.

15. Enhanced Statistical Stability in Coherent Interferometric Imaging, L. Borcea, J. Garnier, G. Papanicolaou and C. Tsogka. Inverse Problems 27 (2011) 085004 33pp.

16. Coherent Interferometric Imaging, Time Gating and Beamforming, L. Borcea, J. Garnier, G. Papanicolaou and C. Tsogka. Inverse Problems 27 (2011) 065008 17pp.

17. Detection and imaging in strongly backscattering randomly layered media, R. Alonzo, L. Borcea, G. Papanicolaou and C. Tsogka. Inverse Problems 27 (2011) 025004 (36pp).

18. Array imaging using intensity-only measurements, A. Chai, M. Moscoso and G. Papanicolaou. Inverse Problems 27 (2011) 015005 (20pp).

19. Correlation-based Radio Localization in an Indoor Environment, Thomas Callaghan, Nicolai Czink, Francesco Mani, Arogyaswami Paulraj and George Papanicolaou. EURASIP Journal on Wireless Communications and Networking 2011, 2011:135 (21 October 2011)

20. Adaptive time-frequency detection and filtering for imaging in heavy clutter, L. Borcea, G. Papanicolaou and C. Tsogka. SIAM Journal on Imaging Science, Volume 4 (2011) pp. 827-849.